Sustainability, through passive solar building envelope design, based on the principles of bioinspiration.

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Abstract. How can architecture respond to sustainability issues where buildings will behave in built environments like living organisms in the natural environment? To answer this question, scientists have turned in recent years to the investigation of living organisms in nature to design models that create new ways to think about adaptation, change, and performance in architecture. At the same time, the development of technologies helps engineers, architects, and designers inspired by bio-mimetics to recreate complex structures that exist in nature, using innovative construction methods and materials, with the aim of energy saving. The building shell is now constructed, not with traditional inert surfaces but with a cladding, which in many cases includes a wide range of technologies based on the behavior of organisms found in nature. The strength of this approach is the identification and evaluation of multiple benefits related to the energy efficiency of biomimetic solutions. The purpose of this article is to create a knowledge transfer between biology and technology and to integrate this knowledge into the development of bio-inspired structures. Thus, three paradigms of kinetic architecture will be presented to understand the importance and impact that the application of bio-inspiration in Architecture can have on the energy debate.

1 Introduction

Buildings that are more energy-efficient and qualified for their immediate surroundings are needed now and, in the future, and they have become an important study topic. It is essential to transform buildings from energy consumers who squander resources into net-zero energy buildings to achieve entire decarbonization inside the buildings. Can kinetic facades inspired by biomimicry, with smart technologies cover the wide range of external environmental changes, including changes affecting heat transfer and solar radiation transmission?

Imani N. and Vale B. [1] claim that problems with energy and climate change have prompted researchers to create nature-based designs that highlight the value of biomimicry in the modern world. The WoS database research showed that there has been a noticeable increase in the number of publications on this subject in recent years. The three countries with the most impact on biomimicry research are Australia, Germany, and the United Kingdom. The university with the most papers and citations is the University of Stuttgart. The majority of the studies focus on building envelopes to regulate various environmental elements using a problem-oriented approach, which was discovered after a thorough study of the publications. According to the results of the studies, biomimicry can provide researchers with innovative concepts for building energy-efficient structures.

A modeled biomimetic approach to deal with promoting the adoption of a shielding shape for eco-friendly buildings and improve the advancement of the building structure is shown in the study by Nalcaci G., Nalcaci G. Modeling [2]. Their shielding type provides comfort for use, maintains the thermal equilibrium for occupants, and contributes to energy consumption via the movement of kinetic cells mounted on the building's exterior. Their design is adaptable to self-supporting building types and can be used as a coating material to lower cooling and heating electricity usage for building facades that will soon be used in smart cities.

To encourage the use of a shielding shape in eco-friendly constructions, this research offers and contrasts three biomimetics models. The shielding type increases energy consumption through the movement of kinetic cells while ensuring user comfort and occupant thermal balance.

2 Related works

2.1 Inspiration from structural color for the design of solar cells.

As shown in Figure 1, a materials science team from Harvard University has invented a fiber that changes color when stretched. Inspired by nature, researchers identified and reproduced the unique structural blocks that create the bright iridescent blue color of a tropical plant flower. Structural paints and superhydrophobicity (Figures 2 and 3) are of great interest due to their unique characteristics. Materials that possess both structural colors and superhydrophobicity are vital for many practical applications. The combination of structural colors and superhydrophobicity can lead to materials for use in various applications, such as sensors, detectors, and humidity actuators, by controlling surfaces to repel or absorb liquids. Regarding super permeability and structural paints, the surface texture and its chemical composition are two factors for making materials with superhydrophobic structural paints [3].

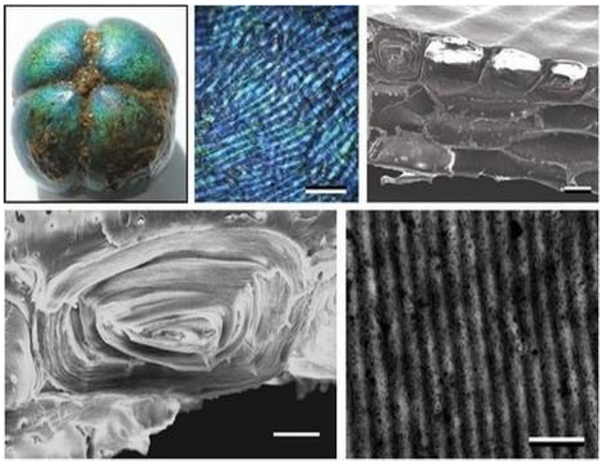

Fig. 1. Bio-inspired color-changing fibers.
http://sco.lt/56EvHF, access 9/6/2023

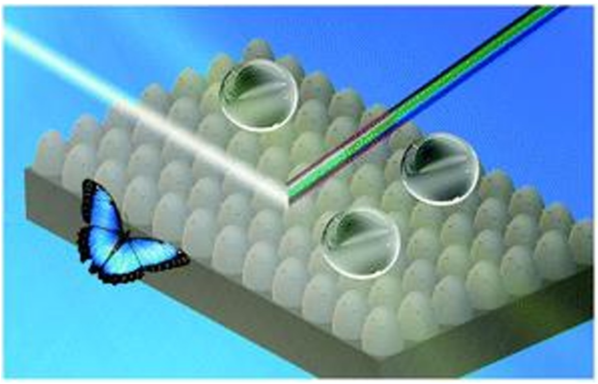

Fig.2. Superhydrophobic surfaces,
www.photonicsviews.com, access 9/6/2023

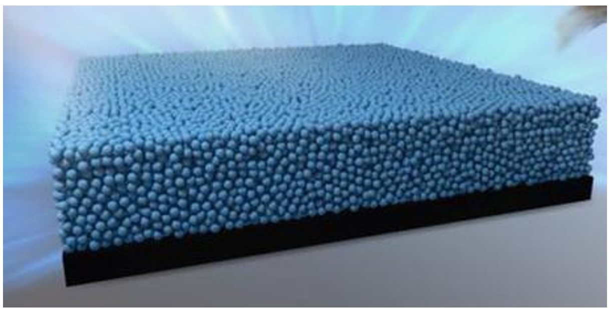

Fig. 3. Superhydrophobic surfaces,
www.photonicsviews.com, access 9/6/2023

Bright colors in the natural world often arise from tiny structures in feathers or feathers that change the way light behaves when reflected. This structural color is responsible for the intense hues in the wings of birds and butterflies. First, by exploiting this effect, we could make new materials for applications such as solar cells. Inspired by the deep blue color of a native North American bird, Stellar's jay, a team at Nagoya University reproduced the color in their laboratory, creating a new type of artificial pigment. According to Yukikazu Takeoka, an outstanding representation of a color structure independent of perspective is found on the wings of Stellar's jay. Dark materials bring out this hue, which in this case has been credited to the presence of black melanin granules in the feathers [4].

In most cases, structural colors appear to change when viewed from different angles, such as the way the colors on the underside of a CD appear to change when the disc is viewed from a different angle. The difference in the blue of the 'Stellar's jay' group is that the light-interfering structures are above black particles that can absorb some of that light. This means that from all angles, the color of 'Jay Stellar' does not change. According to Yukikazu Takeoka, the scientists utilized a layer-by-layer process to produce films of tiny particles that mimicked the bird's wings' small sponge-like texture and black support particles. To mimic the wings, the researchers covered tiny black-core particles with layers of even smaller transparent particles, to make "raspberry"-like particles. The size of the core and the thickness of the layers control the color and saturation of the resulting pigments. According to Takeoka, the color of these particles did not change with the viewing angle, which is significant. The project offers a far more effective means of creating fake structural hues. Although there is still much to learn from biological systems, if we are successful in comprehending and using these phenomena, a plethora of novel metamaterials will be available for a variety of cutting-edge applications where interactions with light are significant [5].

Moreover, researchers at the University of California, Berkeley, have developed an ultra-thin material that can change color by reflecting light at the nanoscale level. This material, which they called "chameleon skin", as Figures 4 and 5 depict, changes color when it is bent or when a small force is applied to its surface [6].

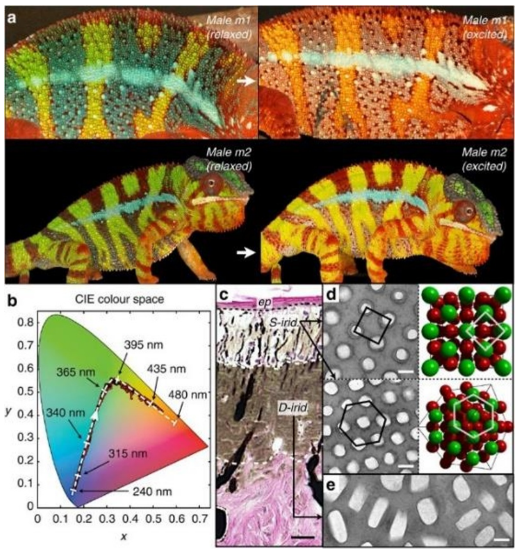

Fig.4. Material that changes color according to needs.
https://onlinelibrary.wiley.com/doi/10.1002/adma.201605050

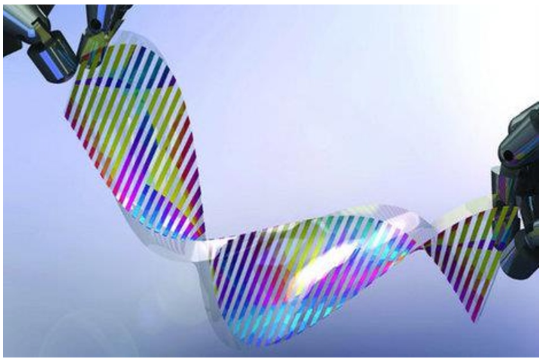

Fig.5. Material that changes color according to needs https://www.nature.com/articles/ncomms7368, 9/6/2023

2.2 Inspiration from the plant growth mechanism for the design of solar cells

An inspiration derived from the mechanism of plants can be applied to optimize the temperature and ventilation quality of buildings.

Nature has created living organisms to interact and relate to their environment. The same goes for plants. The growth and lifespan of plants are strongly influenced by factors such as wind, water, amount of carbon dioxide, and light. Researchers have observed that plants perceive all these factors and use them for growth, physiological and functional response. Interestingly, the researchers found that the leaves during the day have a horizontal orientation, while they appear more or less vertical during the night due to the movement of the enlarged part of the leaves. Leaf movement increases photosynthetic surface area during the day while reducing transpiration water loss during the night. The ability of plants to reject light as an energy source and reuse it whenever they need it is unparalleled [7].

Nature in its strategies and methods of using sunlight to convert it into energy has reached an incredible perfection, which is still not comparable to the current techniques of capturing and converting solar energy. These strategies and methods should be taken as a basic reference. Hug et all said that they are pursuing a series of investigations that still require a lot of work, but that have revealed some pathways, like those of bio-photovoltaic, as shown in Figure 6, and dye-sensitized solar cells: cutting-edge solar cells that can be integrated into a building's facade to simultaneously produce and consume renewable energy [8].

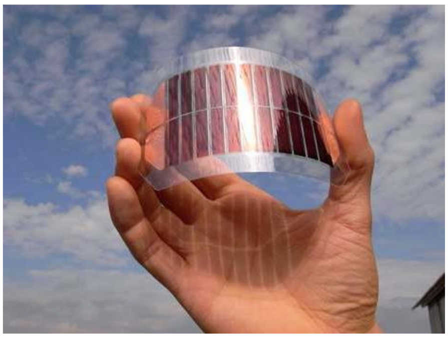

Fig.6. Dye-Sensitized Solar Cells.
(Hug, H., 2014, cited in Di Salvo, S., 2018: 33)

3 Case Studies of Passive solar building design

In this paper, three case studies of Passive solar building design based on the principles of bioinspiration will be presented along with their architectural application and their bioinspiration model.

3.1 Brise soleil

Brise soleil, or "sun breaker", is an architectural feature of a building that reduces heat gain within that building by deflecting sunlight. This system allows the low-level sun to enter a building in the mornings, evenings, and during winter but cuts out direct light during summer. In the typical form, a horizontal projection extends from the sun side facade of a building. This is most used to prevent facades with a large amount of glass from overheating during the summer. Often louvers are incorporated into the shade to prevent the high-angle summer sun from falling on the facade, but also to allow the low-angle winter sun to provide some passive solar heating [9]. Brise-soleil can comprise a variety of permanent sun-shading structures, such as the elaborate wing-like mechanism devised by Santiago Calatrava for the Milwaukee Art Museum, the mechanical, pattern-creating devices of the Institute du Monde Arabe by Jean Nouvel, or the Brise-soleil at the hemispheric of the city of arts and sciences in Valencia, Spain.

3.1.1 Bridge soleil at the Milwaukee Art Museum

Bio-inspiration model: The bio-inspiration model is a bird's wings.

As Figure 7 depicts, the Quadracci Pavilion contains a movable wing-like footing that opens to a 66 m wingspan during the day, folding over the tall, arched structure at night or during inclement weather. There are sensors on the wings that monitor wind speeds, so if wind speeds are above 23 mph for more than 3 seconds, the wings close.

Fig.7. Milwaukee Art Museum with the brise -soleil opened and closed https://www.re-thinkingthefuture.com/case-studies/a3010-milwaukee-art-museum-by-santiago-calatrava-a-spectacular-kinetic-structure/, access 30/7/2023.

There are multiple elements in the structure inspired by its location facing the lake: mobile steel blinds inspired by the wings of a bird, and a curved gallery of a single floor resembling a wave. According to the architect, the design responds to the weather, the sensation of movement, and change. Its shape is functional, controlling the level of light. The striking set of "wings" – the Burke Brise Soleil form a movable sunscreen that can be adjusted throughout the day to shade the interiors of the museum while giving the building a sense of mobility. It takes three and a half minutes for these censor-clad fins to open or close.

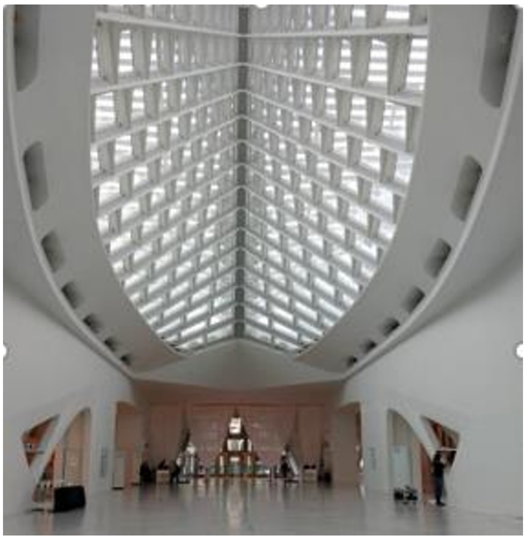

Fig. 8. Structural members of the building https://www.re-thinkingthefuture.com/case-studies/a3010-milwaukee-art-museum-by-santiago-calatrava-a-spectacular-kinetic-structure/, access 30/7/2023.

3.1.2 Bridge soleil at the hemispheric, Valencia, Spain

Bio-inspiration model: The bio-inspiration model is the human eye.

Fig.9. The hemispheric, Valencia, Spain
https://www.visitvalencia.com/en/shop/tickets-to-tourist-attractions/tickets-cac/hemisferic-tickets, access 30/07/2023

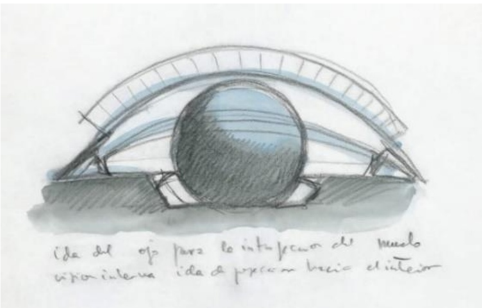

Fig.10. Bio-inspiration model is the human eye
https://www.idesignarch.com/lhemisferic-an-eye-catching-architectural-masterpiece-in-valencia/

As depicted in Figures 9, 10, and 11, built in the shape of the human eye, the Hemisfèric is one of the structures within the City of Arts and Sciences in Valencia, Spain. Designed by architect Santiago Calatrava, the Hemisfèric houses an IMAX theatre, a Planetarium, and a Laserium. The "pupil" is the hemispherical dome of the IMAX theatre, and the "eyelid" can open and close by using hydraulic lifts to operate the steel and glass shutter. This impressive architectural masterpiece is situated at the end of the dried-up riverbed Turia. Calatrava wanted to bring water back to the area by creating a reflecting pool which also serves as a stunning artistic display at night when the lighting creates an image of a whole eye [10].

Fig.11. The hemispheric by night
https://www.idesignarch.com/lhemisferic-an-eye-catching-architectural-masterpiece-in-valencia/,access 04/06/2023

The Hemisfèric was created to represent the 'all-seeing' human eye and the wisdom it represents. It symbolizes looking at and observing the world, the skies, and the stars. A 24.000 square meter glass-bottomed pond surrounds the structure. The relation between the pond and the Hemisfèric becomes apparent when the 'eye' is opened and closed; once closed, the reflection makes the eye look whole and is a mesmeric experience. The shutter built to resemble the closing of an eye is made of elongated aluminum awnings that fold upward collectively to form a brise soleil roof that opens along the curved axis of the eye. The ovoid-shaped roof is more than 100 meters in length and houses a great sphere in which the projection room is located [11].

3.1.3 Flectofin Application

Bio-inspiration model: The bio-inspiration model is the kinematics of plants.
The researchers drew their inspiration from studying the kinematics of plants that have elasticity and do not need linkages. To create a flexible stronger system, it was necessary to get rid of all rigid components. Specifically, they investigated the mechanism by which pollination takes place in the "strelitzia reginae" plant. This plant serves as the natural model upon which the design of

https://doi.org/10.1051/e3sconf/202343601013

Flectofin is based. As depicted in Figure 12, during pollination, the movement of the plant is created by the modification of anatomical and morphological characteristics, which give it the flexibility and elasticity that characterize it.

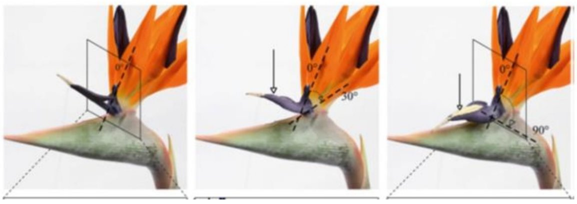

Fig. 12. Elastic deformation in the flower Strelitzia reginae. http://www.simonschleicher.com/flectofin_brochure.pdf

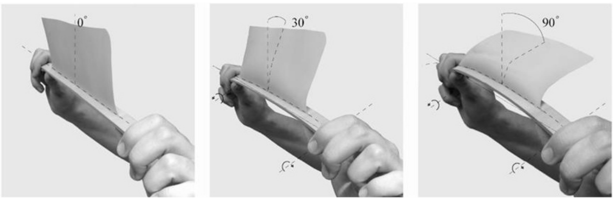

Fig.13. Principle of deformation in the Strelitzia reginae flower, realized with a simple physical model. Bending of the back member causes the attached lamina to deflect up to 90 degrees laterally, i.e., initiated lateral buckling torsion. Left: Closed, lamina at 0°, Right: Open, lamina at 90° [12] http://www.simonschleicher.com/flectofin_brochure.pdf

Close examination of the plant's kinematic mechanisms led the researchers to devise methods that would allow them to move the shutter system to mimic the movement of these plants. In modern times, interactive facade systems with smart blind systems have become popular. However, these facade systems require maintenance continuously as they are not independent of mechanical hinges. On the other hand, Flectofin's blind system is made of soft materials that can be easily designed on 3D printers, without the need for hinges for support. Growing structures can be expanded and shrunk due to their geometric, material, and mechanical properties, offering the possibility to create truly transformed environments, leading to a dynamic Architecture [13].

All plants found in nature move, shift, and bend without support from hinges of any kind. Different plants have different elastic ranges depending on their construction; however, the movement of each plant is reversible. Sunbirds feed on nectar and pollinate the Strelitzia reginae plant. The flower makes a 90o angle with the stem acting as a prominent landing point for the bird. The shape and structure of the Strelitzia reginae flower is such that as the sunbird lands on the projecting part of the flower the petals at the bottom are pulled down, exposing the anthers. The pollen contained in the exposed anther sticks to the bird's legs as it feeds on the nectar, and so when the bird lands on another flower, the pollen that covers the bird's legs is deposited on its petals. By researching this whole process, the researchers learned the mechanism of the plant which they copied in the design of the hinge-less "Flectofin louver" system structure [14].

Flectofin was designed by an interdisciplinary team consisting of biologists, architects, and engineers to be a kind of blind system. As depicted in Figures 14 and 15, Flectofin works without hinges and can be easily rotated to a 90-degree angle. The system achieves this flexible rotation by simulating a change in temperature or displacement of the material supporting the plate which causes it to bend from the pressure of the forces thus produced. Flectofin fins can be moved 90 degrees in any direction, with precise adjustment to any angle in the range of 0 to 90 [12].

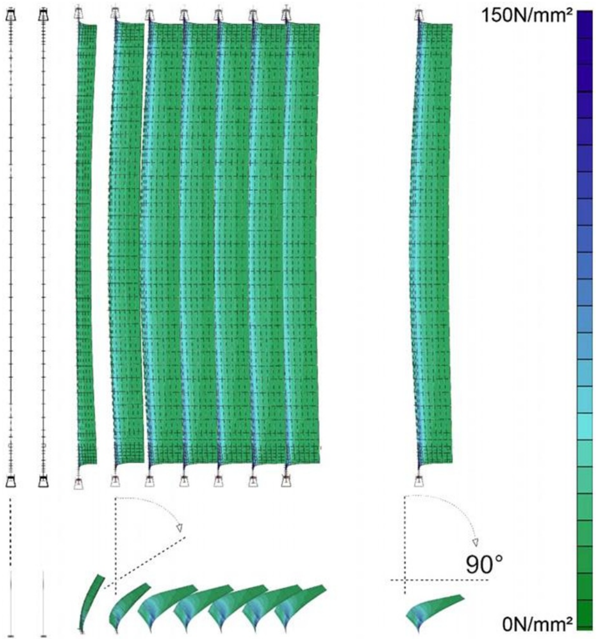

Fig.14. Simulation of the kinetic structure in finite elements showing consequent deformation of the element due to bending in the backbone and the corresponding residual stress. https://www.researchgate.net/publication/51839563_Flectofin_A_hingeless_flapping_mechanism_inspired_by_nature

Fig. 15. Prototype of the Flectofin R shading system, in 1:1 scale, produced with industrial project partner Clauss Markisen (CM). Made of GFRP (height = 2 m, width = 0.25 m, and

thickness = 2 mm), the lower support can move vertically and thus causes the eccentrically connected beam to bend. GFRP: (Glass Fiber Reinforced Polymer) polymer reinforced with glass fibers.
https://www.researchgate.net/publication/51839563_Flectofin_A_hingeless_flapping_mechanism_inspired_by_nature

3.1.4 Architectural application - the 'One Ocean' pavilion at EXPO 2012, Yeosu

The main objective of the 'One Ocean' building for EXPO 2012 in South Korea was to protect residents from environmental factors. This is achieved by using technologies that make the building facade dynamic so that it adapts to environmental conditions.

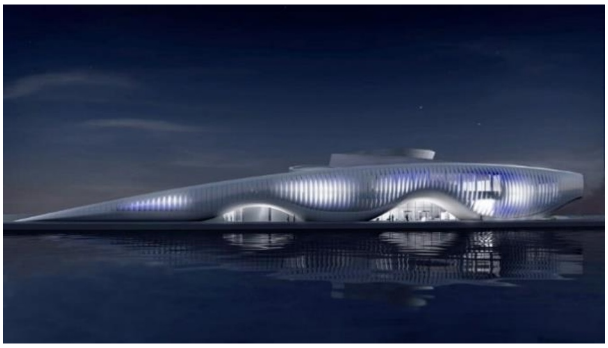

Fig.16. «One Ocean», EXPO 2012, South Korea https://www.archdaily.com/208700/in-progress-one-ocean-soma , access 9/2/2023

As shown in Figure 16, the themed pavilion at Expo 2012 in Yeosu, is a kinetic facade system consisting of 108 laminated glass fiber-reinforced polymers (GRFP) that move to create a variety of patterns. The blades are driven by a screw, which is attached to a high-precision motor. Opening and closing the blinds control the lighting in the interior, acting as an interactive window. Each slat has a special actuator, allowing individual control of the slats. Synchronization in the movement of the actuators is achieved by a central computer. The actuators produce compressive forces at the ends of the fins, causing them to bend in an elastic manner similar to Flectofin. During this process, a part of the activation energy is converted into electrical energy. Electricity is produced during the closing process using the motors acting as electrical generators [15]. As depicted in Figures 17 and 18, the opening of the angle of the blinds is related to their length: the greater the length of the slat, the greater the area that is illuminated and therefore the resulting spectacular effect [16].

Fig.17. Cinematic facade of EXPO 2012-themed pavilion in Yeosu, South Korea. With closed slats, Architects: soma-architecture.https://transsolar.com/projects/one-ocean-pavillon-expo-2012, access 09/2/2023

Yeosu's climate is characterized by three main seasons: a cool winter, a hot and humid summer, and moderate periods in between. The building's adaptive kinetic facade improves natural ventilation by capturing and directing winds into the building during moderate and non-humid interseason.

Fig.18. Facade with open slats, Architects: soma-architecture. https://transsolar.com/projects/one-ocean-pavillon-expo-2012, access 09/6/2023

During this time, the floors are cooled directly via a seawater heat exchanger. As shown in Figure 19, in high summer conditions, supply air dehumidification and radiant floor cooling are supplied by high-efficiency cooling condensers connected to the seawater heat exchanger. During the winter, these chillers are set to heat pump mode and use seawater as an energy source to generate heat for the radiant floors and mechanical ventilation system. Photovoltaic panels are integrated into the roof to generate solar electricity, providing approximately two-thirds of the energy consumed by building systems during the year [17].

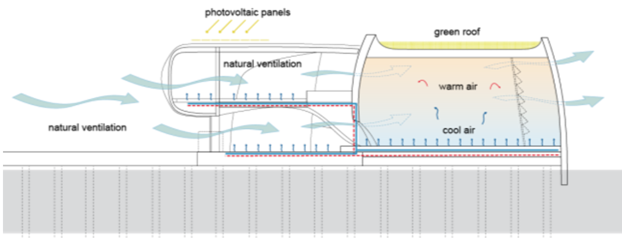

Fig.19. Section of plans showing the existing climate design concept for the pavilion, https://transsolar.com/projects/one-ocean-pavillon-expo-2012 , access on 9/2/2023

4 Discussion and Conclusions

This study aims to present the big impact the building envelope has on energy efficiency and especially on solar radiation control. Building envelopes plays a significant part in either improving or deteriorating the state of the global climate, according to several assessments. Energy efficiency is one of the most crucial criteria used to assess if sustainable design has been achieved.

The major advantage of bioinspiration design building envelope is the energy optimization through the development of adaptive façade technology.

Moreover, the biomimetic approach of the kinetic facades tries to connect the building with its environment, thus, having comfortable, even temperatures all year round and making good use of natural light. It will therefore require less energy to heat, cool, and illuminate than a conventional building. Hence it will also create less greenhouse gas emissions helping the environment. Passive solar energy requires buildings to be located and designed so that they interact with the environment and climate positively and the biomimetic approach of the kinetic facades enhances this purpose.

Additionally, bioinspiration façades not only contribute to the aesthetic appearance of buildings but also improve the visual comfort of occupants, leading to increasing satisfaction. Although not every biomimetic adaptive application is sustainable, the concept of biomimetics is in harmony with the concept of sustainability.

Finally, the outcomes of the research presented in this article show that the most common type of shading systems, which can be either blind with the option of opening or dynamic shading, are being developed for a new generation of buildings with extremely high technological aspects that are sustainable in their behavior. These materials and technologies can respond and react to changes in their environment. The building's energy requirements are reduced because of the new dynamic models based on biomimicry concepts, sensors, and smart technologies, by controlling solar radiation. Because of this, the building envelope should no longer be a static load-bearing structure but rather, like the skin of a living thing, serve as a dynamic mediator between the interior and exterior environments.

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